

High Altitude Molecular Clouds

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ABSTRACT

A population of molecular clouds with a significantly greater scale height than that of Giant Molecular Clouds has been identified by examining maps of the latitude distribution of the $^{12}CO(1 - 0)$ emission in the first quadrant of the Galaxy. These clouds are found by identifying emission more than 2.6 times the scale-height away from the galactic midplane (centroid of CO emission) at the tangent points. Since the distance to the tangent points is known, we know the height and the sizes of these clouds. They are smaller and fainter than the GMCs and do not seem to be gravitationally bound. These clouds have properties similar to the high latitude clouds in the solar neighborhood. Although they lie outside the molecular cloud layer, the high altitude clouds are well within the HI layer in the Galaxy and coincide with distinct peaks in the HI distribution. These clouds represent a galaxy wide population of small molecular clouds having a larger scale height. They may be clouds in transition between molecular and atomic phases.

Subject headings: interstellar, molecules, molecular clouds, Galaxy

1. Introduction

Molecular gas is confined to a layer much thinner than the stellar disk, and if isothermal, is expected to have an equilibrium distribution which is Gaussian in z (Spitzer 1942). This layer seems to be Gaussian from the various surveys of molecular gas in the galactic plane (Sanders et al. 1986, Clemens et al. 1986, Cohen et al. 1986, Bronfman et al. 1989, Dame et al. 1987). Since the molecular gas forms a cold, thin layer in the disk, it may be possible to look for signatures of disequilibrium in departures from Gaussianity of the distribution.

These departures from a Gaussian distribution in z could be due to violent events stirring up the gas (for example supernovae) and subsequent formation of molecular clouds in swept-up shells, or to short lifetimes of molecular clouds, or to infalling gas etc.

Alternatively, they might reflect the existence of more than one population of molecular clouds with different (cloud-cloud) velocity dispersions and hence different scale heights in equilibrium.

We have systematically searched for and found a population of small clouds lying at high altitudes away from the galactic plane. These clouds are identified in the $^{12}CO(1 \rightarrow 0)$ survey of Knapp, Stark & Wilson (1985). This survey combines a wide latitude coverage (typically $\pm 2^\circ$) with close sampling in latitude ($\Delta b = 2'$).

The clouds are identified at the tangent points where we know their distances and hence can determine their height above the galactic plane. The vertical distribution of CO emission at tangent points, i.e. the scale height and mid plane positions have been measured by Malhotra (1994, hereafter paper I). The data and the model fits to are described briefly in section 2.1 and 2.2. In section 2.3 the selection criteria for the identification of the high altitude clouds (HACs) are described. Section 2.4 quantifies the dependence of assumed distances on the cloud random velocity. Most of the clouds cannot be made to belong to the galactic plane population without having equally improbable peculiar velocities ($> 3\sigma_V$; where σ_V is the cloud-cloud velocity dispersion).

Molecular clouds have been found at high galactic latitudes by Magnani, Blitz & Mundy (1985), Keto & Meyers (1986). Molecular gas has also been found associated with cirrus at high latitudes by Desért et al. 1988, Heiles et al. 1989 and Desért et al. 1990. Clemens and Barvainis (1988) have compiled a catalog of small clouds in the galactic plane. It would be logical to compare the properties of the clouds found at high z with the local High Latitude Clouds (HLCs) and the Giant Molecular Clouds to see if the HACs are well separated in their properties from the other molecular clouds. In contrast to the HLCs and the Clemens-Barvainis (CB) objects the HACs are not selected by optical extinction/infrared emission but by CO emission. The population of HACs is intermediate in its properties between GMCs and the local high latitude, high velocity molecular clouds associated with infrared cirrus and the CB clouds. Part of this may be due to the different selection criteria. Section 3 describes the properties of the HACs.

Even though these clouds are at greater distances from the plane than expected from the scale height of molecular gas, they still are well within the atomic gas layer, which has about twice the scale height of molecular gas. The ^{12}CO survey by Knapp et al. (1985) from which the HACs are selected was carried out at the same longitudes as the HI survey at Arecibo (Bania & Lockman 1984). We compare the properties of the molecular gas (as measured by the $^{12}CO(1 \rightarrow 0)$ line) and HI (in the 21 cm transition) at the locations of HACs in section 3.

2. Cloud Identification

2.1. The data

We search for high altitude clouds in the $^{12}CO(1 \rightarrow 0)$ survey that Knapp et al. (1985) obtained using the 7 meter antenna at Bell Laboratories. The data and details of the survey and the instruments are presented by Knapp et al. (1985).

The survey consists of 38 strip maps (in latitude) of the $^{12}CO(1 \rightarrow 0)$ line emission. The strip maps were taken at longitudes between 4° and 90° , spaced at equal intervals in the $\sin l$, $\Delta \sin l = 0.025$. The maps are sampled at intervals of $\Delta b = 2'$ with a half-power beamwidth of $100''$. The latitude coverage is $\simeq \pm 2^\circ$, varying slightly from one line of sight to another. The latitude extent is more than adequate for studying the tangent point emission (except possibly for $l \geq 60^\circ$), and extends more than three scale heights both above and below the centers of distribution in more than half the lines of sight. The extent of the survey beyond three scale heights at the tangent points is uneven because the molecular gas layer deviates significantly from $z=0$.

The velocity resolution is 0.65 km s^{-1} . The rms noise is typically 0.3 K but varies slightly in each latitude strip. In addition the $^{13}CO(1 \rightarrow 0)$ line was mapped with noise levels of 0.1 K for two longitudes ($l=28.36$, $l=77.16$)

We also use the HI survey of Bania & Lockman (1984) at Arecibo done at the same longitudes as the CO survey, starting $l \simeq 31$. The HPBW in the 21 cm line is $4'$ and the maps were sampled at intervals $\Delta b = 2'$. The velocity resolution is 1 km s^{-1} .

2.2. The vertical distribution of the molecular gas

The vertical distribution of gas at tangent points was modeled for more than half (23 out of 38) the observed lines of sight. The low longitude ($4^\circ < l < 17^\circ$) maps were unusable due to the lack of emission at (or reasonably near) the tangent point velocities. The high longitudes ($l > 61^\circ$) maps were unusable because their tangent point emission is at low velocities and is contaminated by emission in reference positions; and because the latitude extent of the maps is not adequate for this (almost) local emission.

Assuming an axially symmetric model of the inner galaxy, we can obtain distances to the tangent points, and from the data find the distribution of the molecular gas in z . We

model the distribution as a Gaussian in z ,

$$\rho(z) = \rho(0) \exp\left(-\frac{(z - z_0)^2}{2\sigma_z^2}\right)$$

fitting both the scale height σ_z and the centroid z_0 . Examples of best fit models are shown superposed on the data in Figure 1.

The models are shown as contours of equal temperature in latitude l and velocity V . While the z -profile is a Gaussian at each radius, the contours appear to be more complex because the velocity structure near the terminal velocity must take into account the velocity dispersion of the gas and the obtrusion of emission from gas near the tangent points. The details of the modeling are given in Paper I.

2.3. Cloud identification

After fitting the Gaussian distribution in z , we identify clouds that are more than $2.57\sigma_z$ (corresponding to a two-sided significance level of 1%) away from the center of the distribution as High Altitude Clouds (HACs). Since the rms noise is different for each spectrum, detections are based on the rms noise of each spectrum, as calculated from the part of the spectrum at velocity $V > (V_T + 3 \sigma_V)$; where V_T is the terminal velocity and σ_V is the velocity dispersion (determined in paper I). In figure 1, the points on the b - v diagram denote detections. To be considered at all the cloud must be detected in more than one adjacent velocity channel and at more than one adjacent latitude. This imposes a selection effect of detecting clouds with velocity widths $> 1.3 \text{ km s}^{-1}$ and a cross-section in $z > 9.6 \cos l \text{ pc}$. There exists only one cloud more than $2.56 \sigma_V$ away from the tangent point velocity and that cloud also is an outlier in z ($l=58.21$, $z=153$, $V=53.3$).

2.4. Kinematic distances

In the above discussion the distances have been determined kinematically, i.e. the gas at extreme velocities is assumed to be at the tangent point distances (assuming circular symmetry). These distances could be incorrect due to deviations from orderly circular rotation of the galaxy. Since we identify high altitude clouds by the ratio of their distance from the center of distribution z_0 to the scale height of the distribution, these clouds are outliers (but with different z) if the high and low z gas have similar kinematics. For example if the gas is moving on elliptic rather than circular orbits, the vertical scale of a particular tangent point emission is not correct but the ratio of z to the scale height σ_z is.

These assumptions break down if the kinematics of the HACs are different from those of the GMCs. High (positive) peculiar velocities of (relatively) nearby clouds could lead us to misidentify the clouds as belonging to the tangent point population and overestimate their distances (and heights above the plane). Figure 2 shows the peculiar velocity needed by each cloud to be at a smaller z , versus the reduced height z in units of σ_z .

Given that the cloud-cloud velocity dispersion is $5 - 10 \text{ km s}^{-1}$ (Clemens 1985, Stark 1984, Stark & Brand 1989, Magnani, Blitz & Mundy 1985, Malhotra 1994) figure 2 shows that the peculiar velocities needed to bring many of the HACs close enough to belong to the GMC cloud population are improbably high.

3. Properties

3.1. Distribution

Each of the 23 lines of sight analyzed should have two regions (one above and one below the galactic plane) where one can find HACs, making 46 regions in all; of these 40 regions are covered in the the survey of Knapp et al. (1985) and 23 clouds were found, yielding a probability slightly above a half of finding an outlier to the population. These numbers however should be interpreted with care as the clouds are identified as spatially and kinematically distinct entities on the basis of 3σ detection levels. There are many instances of a group of clouds very close in the b - v space and also lying within the same clump of HI. Any one such group may be a set of multiple peaks of a faint cloud.

The highest altitude at which a cloud is found is 212 pc (about four times the average scale height of molecular gas). Of the 23 HACs, most (18) lie within four scale heights from the center of the distribution, and two are $\simeq 5.2\sigma_z$ away. The z -distribution of HACs is given in figure 3.

3.2. Properties

Since this sample of clouds is identified from b - v maps, their properties (e.g. size) are derived from a single cross-section in z , i.e. a random chord through the cloud. For a more reliable size and mass estimate the clouds should be mapped in l and b . Most of the clouds are smaller than GMCs (giant molecular clouds). The smallest cloud we can detect varies with the longitude. At $l = 58.21^\circ$, for example, a cloud must be $\geq 5 \text{ pc}$ to be detected in

more than one latitude scan. The largest and the smallest clouds found are 6.8 and 37 pc in extent (in z). From figure 4 we see that the sizes of the HACs are distributed in the region between the detection limits and the typical sizes of GMCs. The size spectrum is consistent with the size spectrum of GMCs extrapolated to smaller sizes. Figure 4 shows a histogram of the observed size distribution of the HACs along with the relative numbers of HACs expected in each size bin if they had the size spectrum of GMCs ($dn(R)/dR \propto R^{-2}$) (Solomon and Rivolo 1989) normalised to the number of HACs found in the smallest size bin.

The size-linewidth relation seen to be valid for the GMCs (Dame et al 1986) $\sigma_v^2 \propto R$ is not valid for the HACs. There exists a very weak correlation between the size of the cloud and its velocity dispersion (figure 4) and the slope of the correlation is different; $r \propto \sigma_v^{0.5}$.

The mass is estimated using the standard conversion factor $X = N(H_2)/I(^{12}CO) = 3.0 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$. Considering that we are taking random chords through a cloud and the expected length of a chord is $(\frac{4}{3}r)$ for a spherical cloud of radius r , the mass of the cloud is given by $M(H_2) = 3 \times (R/\text{pc}) \times \int I(^{12}CO) dz dv$. The largest mass found is $5.4 \times 10^3 M_\odot$ and the smallest $42 M_\odot$.

The internal velocity dispersions range from 0.49 km s^{-1} to 5.8 km s^{-1} . The observed velocity dispersions are higher than the velocity dispersions derived using the cloud masses, cloud sizes and the virial theorem. Table 1 gives the ratios of the observed velocity dispersion and the virial velocity dispersion; this ratio is significantly higher than 1 for HACs. (It is about 1 for GMCs). Note that the $\sigma_V(\text{virial})$ depends on $\sqrt{M/R}$ and (M/R) is the integrated luminosity of the cloud in a b-v map. Therefore $\sigma_V(\text{virial})$ is a measured quantity. These ratios shows that either these clouds are not bound by their own gravity, or they have a different conversion factor X.

For the line of sight at $l = 28^\circ$, the HACs are also found to have a higher ratio of ^{12}CO and ^{13}CO intensities, $R = I(^{12}CO)/I(^{13}CO)$, than the low altitude clouds (cf Polk et al. 1988). $R = 9.5$ for HACs, higher than the value for galactic plane clouds; $R = 4$ for the clouds in this sample, and $\simeq 3 - 6$ for GMCs (Gordon & Burton 1976; Solomon, Scoville & Sanders 1979). Mass estimate from ^{13}CO observations would make the discrepancy between the virial mass and the mass inferred from ^{13}CO more pronounced as the velocity dispersions in the two lines are comparable and the $^{12}CO/^{13}CO$ ratio is larger for HACs.

For comparison the local high latitude cloud population has an average size of 1.6 pc, average mass $40 M_\odot$ and internal velocity dispersion between 0.11 km s^{-1} and 3.2 km s^{-1} (Magnani et al. 1985). All the high latitude clouds whose distances are known lie within 3 scale heights of the disk so they are not outliers in the z-distribution (Blitz 1990).

3.3. Atomic envelopes

Atomic and molecular gas show similar large scale distributions and kinematics in the inner galaxy (e.g. Burton & Gordon 1976). Comparing the b-v maps of CO and of HI taken at the same longitudes, both the galactic plane and the HACs coincide in space (z-distribution) and approximately in velocity with HI maxima. Figure 6 shows the CO and the HI emission maps superimposed. The atomic gas associated with the HACs has greater altitude and velocity extent than the HACs. Table 1 gives the mass of HI associated with a HAC or a group of HACs. In many cases (e.g. at $l=46$, figure 6) the HACs have a slightly different velocity than the peaks of HI surrounding them. The mass of the HI associated is found to be less than the mass of the molecular gas.

4. Discussion

In the previous sections we have established that there exist clouds making up the higher-than-Gaussian tails of the vertical distribution of molecular gas. The anomalous heights of most of these clouds cannot be explained by small discrepancies in kinematics (such as random motions of clouds). Besides, most of these clouds correspond (in z-position and velocity) to distinct maxima in HI and are well within the HI layer.

The High Altitude Clouds are seen to cover much of the range between the GMC's and the local high latitude clouds, in their properties. The requirement that emission be detected in at least two adjacent latitudes places a lower limit of $\simeq 30 M_{\odot}$ on what we would identify as a cloud. With the number of clouds we have, the size-mass parameter space seems filled. The size of the clouds varies from $\simeq 7$ pc to 37 pc. The mass varies from $\simeq 43 M_{\odot}$ to $5.4 \times 10^3 M_{\odot}$. The velocity dispersion covers the range 0.5 and 5.8 km s^{-1} . Compare this to the local high latitude clouds which have an average size of 1.6 pc, average mass $40 M_{\odot}$ and internal velocity dispersion between 0.11 km s^{-1} and 3.2 km s^{-1} (Magnani et al. 1985) and the local GMCs which have a typical mass $1 - 2 \times 10^5 M_{\odot}$, diameter 45 pc and velocity dispersion 2 km s^{-1} .

In spite of their small sizes these clouds do not in general have a simple velocity structure. Also they are not self-gravitating. Most of the clouds need to be more massive by about a factor of 25 to be in virial equilibrium. Again one must take into account the selection of clouds having velocity widths of $> 1.3 \text{ km s}^{-1}$, so the small clouds that are in virial equilibrium are not detected. The present sample of clouds could be in virial equilibrium if they were elongated in the direction of the galactic plane with median axis

ratios of 25. The HACs could be virial equilibrium if the $N(H_2)/W(^{12}CO)$ conversion factor was higher for these clouds. We have calculated the masses using the $N(H_2)/W(^{12}CO)$ conversion ratio derived from galactic plane GMCs. It is possible that this factor changes with the height above the galactic plane. For example this factor is inferred to be higher for outer galaxy, i.e. the outer galaxy clouds are underluminous in ^{12}CO (Mead & Kutner 1988). There are two reasons why we believe the mass derived from CO luminosity rather than the virial mass. First the metallicity gradient invoked for the high X value for outer galaxy molecular clouds is perhaps not be justified for HACs which are a mere 200 pc away from the galactic plane, and there is no evidence of metallicity gradient on that scale. Second the tight correlation between $M(CO)$ and the velocity dispersion that is seen for the outer galaxy clouds ($M(CO) \propto M(\text{virial})$) is not seen here. de Vries et al. (1987) have argued for a lower value of $N(H_2)/W(^{12}CO)$ for the diffuse molecular gas associated with the high latitude cirrus on the basis of its infrared emission. The HACs could thus have a smaller $N(H_2)/W(^{12}CO)$ ratio exacerbating the discrepancy between $M(CO)$ and $M(\text{virial})$.

While there is atomic gas associated with the clouds, the mass of the HI associated is typically smaller than the mass of H_2 . The atomic gas associated is not enough to gravitationally bind the molecular clouds. For the one line of sight where ^{13}CO was also observed the ratio of $^{13}CO/^{12}CO$ decreases as we move out of the galactic plane (Polk et al. 1988), indicating that the high altitude molecular gas is more diffuse.

Embarrassingly enough one can think of too many explanations for the presence of high z clouds. Characteristic crossing time for the vertical movements of clouds through the Galactic plane is $\sim 10^8$ years, whereas the interstellar medium is stirred by supernova explosions every $\sim 10^7$ years or so. If molecular clouds form in the Heiles-type shells-supershells (Heiles 1979), it can explain the presence of HACs. The HACs would then appear along the arcs in l-b plane corresponding to the supershells. We cannot test this in the present data set which is sparsely sampled in longitude. For the galactic plane gas the shells may be difficult to disentangle as the HACs are still well within the HI layer ($|l| < 3^\circ$).

The HACs could also be a separate population of clouds with a different scale height, but in vertical equilibrium in the galaxy by having a higher cloud-cloud velocity dispersion. It has been suggested by Stark (1983) that smaller clouds have greater scale heights. HACs are smaller than the GMCs, so a higher velocity dispersion would go along in the direction of their having some equipartition of energy (but not large enough to go as $M^{-0.5}$). With our sample of 23 clouds it is difficult to test if these clouds have a higher velocity dispersion. However they are coincident in space and velocity with HI peaks and HI shows an increase in velocity dispersion with height above the plane (Kulkarni & Heiles 1987). A separate

acceleration mechanism for small and large clouds could also lead to different scale heights. There are no characteristic sizes pointing to a bimodal distribution that one expects of two separate populations. For a continuously smaller and hotter (higher velocity dispersion) population of clouds we should see a correlation between the size and the height above the plane of the HACs. Such a correlation is not seen for this sample.

Another possibility is that in the HACs we might be witnessing the formation/dissolution of molecular clouds as they pass from the galactic plane to less dense regions or vice versa. The lower H_2/HI ratio and $^{13}CO/^{12}CO$ show that the clouds are less dense than the galactic plane clouds. Lack of virial equilibrium further points to these clouds being transient objects.

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Figure 1: The latitude-velocity contour maps for the longitudes (indicated at the top right hand corner) where high altitude clouds are detected. The contour levels are (1.2, 1.6, 4 K). The best-fit model of tangent point emission is superimposed (contour levels at 0.2, 0.4, 0.6, and 0.8 times the peak temperature). Points denote detections at the 3σ level. Broken lines denote $2.57\sigma_z$ from the centroid of the z -distribution. A cloud is identified by detection in more than one adjacent velocity channels and more than one latitude. A High Altitude Cloud is a cloud found more than $2.57\sigma_z$ away from the local midplane in the tangent point region (velocities greater than the cutoff velocity indicated by the vertical line). The blow-ups of the HACs show that many do not have a simple geometry or a simple velocity structure.

Figure 2: For each cloud in the sample the peculiar velocity needed to reduce the height estimate is plotted against the reduced height in units of σ_z . A (relatively) nearby cloud with a large positive positive velocity could be mistaken for a tangent point cloud. In such a case the distance is overestimated so the height above the plane is also overestimated. In this plot each line represents a High Altitude Cloud. The overestimate of height is plotted against the velocity needed to produce that overestimate. A large number of clouds need an improbably large velocity (more than $3\sigma_v$, where σ_v is the cloud-cloud velocity dispersion) to have been misidentified as outliers in z .

Figure 3: The vertical distribution of High Altitude Clouds is shown in units of (a) $|z/\sigma_z|$ and (b) z . The most outlying clouds are $\simeq 5.2\sigma_z$ from the midplane, and the highest cloud is at $z = 212$ pc.

Figure 4: The size distribution histogram of the High Altitude Clouds detected. The biggest cloud is 37 pc and the smallest is 7 pc. The size-spectrum of Giant Molecular Clouds ($dn(R)/dR \propto R^{-2}$) normalized to the number of clouds in the smallest bin is shown by the curve. The High Altitude Clouds have the same size spectrum as the GMCs.

Figure 5: The sizes (z cross-sections) versus the velocity dispersions of the High Altitude Clouds. There is a weak size-linewidth correlation. The solid line shows the best fitting correlation $R \propto \sigma_v^{0.5}$. The dotted line shows the size-linewidth relation for Giant Molecular clouds $R \propto \sigma_v^2$.

Figure 6: The latitude velocity contour maps for HI (light lines) and CO (dark lines). The contour levels are (10, 20, 30, 40, 50, 60, 70, 80, 90, 100 K for HI) and (1.2, 1.6, 2, 3, 4, 6, 8, 10, 12 K for CO). There is close correspondence in the positions and velocities of CO emission with HI peaks both for galactic plane CO as well as for most of the High Altitude Clouds.

Figure 7: The latitude velocity contour maps of $^{12}CO(1 \rightarrow 0)$ (shaded areas) and

$^{13}CO(1 \rightarrow 0)$ emission (contours: 0.4, 1.2, 4 K) at the longitude $l = 28.36^\circ$. There is ^{13}CO emission detected for both galactic plane clouds and the high altitude clouds. The ratio of ^{12}CO to ^{13}CO however is higher for the High Altitude Clouds as seen from the side panel which shows ^{12}CO (thin lines) and ^{13}CO (thick lines) emission integrated over tangent point velocity range (indicated by arrows).

Table 1. Properties of the clouds

l ($^{\circ}$)	z (pc)	Δz (pc)	V (km s^{-1})	σ_V (km s^{-1})	M_{H_2} (M_{\odot})	$\frac{\sigma_V}{\sigma_V(\text{virial})}$	M_{HI}^1 (M_{\odot})
23.58	-148	8.9	99.4	1.63	90	11.2	...
23.58	-212	8.9	104.4	0.69	60	5.8	...
25.25	158	8.9	101.8	0.70	82	5.1	...
25.25	101	8.9	105.9	0.74	99	4.8	...
28.36	74	12.9	96.7	1.92	685	5.9	...
28.36	65	12.9	102.3	0.73	1109	1.7	...
30.0	80	25.4	95.1	1.93	1587	5.5	...
33.37	81	36.9	99.1	2.19	4808	4.4	1096
33.37	-122	8.2	79.9	0.70	52	6.4	...
33.37	-197	20.5	81.2	0.74	642	3.0	105
38.68	167	7.6	81.8	1.04	123	6.2	...
38.68	135	7.6	72.4	2.32	1193	4.4	1067
38.68	109	15.2	74.2	0.74	215	4.7	1067
44.43	66	35.2	59.0	1.92	3622	4.7	350
44.43	-195	24.6	70.5	1.04	540	5.5	...
46.47	108	6.8	48.6	0.68	43	6.8	299
46.47	97	13.6	57.1	2.40	1665	5.5	299
46.47	-156	34.0	57.6	2.94	3425	7.3	335
46.47	-201	6.8	64.4	0.67	54	6.0	...
55.59	-88	24.6	46.8	5.80	5464	10.9	1167
58.21	153	12.9	53.3	1.70	956	5.7	188
58.21	-84	7.8	45.2	1.72	389	6.9	214
58.21	-136	7.8	38.7	1.00	119	7.3	...

References. — (1) Identical HI masses in two consecutive rows mean that the two molecular clouds share the same atomic envelope